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Review

Bamboo in the pulp, paper and allied industries

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ABSTRACT

Bamboo, a member of the grass family, is a fast growing and high yielding renewable resource. The popularity of bamboo has risen in recent times owing to its multifaceted and myriad of practical applications. There are unlimited uses of bamboo, therefore proper utilization of this beneficial resource will be useful to the industrial sector. This review provides a comprehensive summary regarding the potential of bamboo as a vital non-wood fibrous raw material for pulp, paper and other allied industries owing to its ability to conserve forests and foster sustainable economic development. Bamboo's abundance, renewability, mechanical strength, and other functional features make it an appealing and potential building biomaterial in the pursuit of sustainable raw materials needed for industrial development. This review provides an in-depth summary and unique perspective on the application of bamboo at a commercial scale in various sectors, thereby encouraging the utilization of this potential material towards environmental sustainability and economic growth.

1. Introduction

Bamboo is a key Non-Timber Forest Product (NTFP) belonging to the Poaceae family (sub-family Bambusoidae), and consists of a diverse group of species. This perennial, mostly evergreen, grass is,one of the fastest growing plants, making it an appropriate choice for the production of valuable green products such as fuels, chemicals and biomaterials (Rathour et al., 2022). The versatility of the bamboos means that they have immense economic and environmental significance, with many species also possessing high strength and toughness (Zheng and Zhu, 2021). This natural material has high biomass productivity, with some species having about 10–30% increment in biomass per day and a short harvesting cycle of 3–4 years. Wood, in comparison, has only 2.5%, and a harvesting cycle of 8–20 years for fast growing woody species such as *Schima wallichii* (or Needlewood) (Siregar et al., 2023). Bamboo species exhibit an impressive annual biomass growth estimated between 22 and 44 million tons per hectare per year, surpassing that of pine forests (25–30 million tons per hectare per year) and matching the productivity of eucalyptus forests (30–40 million tons per hectare per year) (Rathour et al., 2022). The height growth varies from around 20.32 cm per day for some species to about 50 cm each day for fast growing ones (Yadav and Mathur, 2021). Bamboos tend to have relatively good contents of holocellulose (Yusuf et al., 2018). They have an exceptional ability to adapt to varied climatic and edaphic conditions and can grow in extremely diverse soil conditions, varying from organically poor to mineral rich. They also have a broad range of moisture tolerances, which makes them an effective tool for the reclamation of degraded land. Bamboos have been shown to play an important role in carbon sequestration and biodiversity conversation.

The complex system existing in bamboo plant comprises of dual set of similarly structured vegetative axes, one occurring above (culm) and the other (rhizome) present below the ground (Sakaray et al., 2012). Woody culms, a complex branching system, strong rhizome structure and infrequent flowering are all distinguishing characteristics of the non-herbaceous bamboos in the Bambuseae and Arundinaieae clades (Tewari et al., 2019). Culms are considered the most useful part from the view of industrial utilization (Anokye et al., 2016). Bamboos are monocotyledonous without secondary growth which means that they have only longitudinal growth, with none of the lateral or radial growth that is found in trees. The culms have solid, swollen segments called nodes and the area between two consecutive nodes is known as an internode. Generally, the internodal length increases with height along the culm until the middle and then decreases. The internodal length varies from 5 to over 60 cm depending on the species (Sakaray et al., 2012). Bamboo is heterogeneous in its anatomical structure. It is principally composed of two kinds of tissues i.e., fibres and vessels, which are organized in clusters of fibrovascular bundles loosely scattered in a continuous parenchymatous medium. The average fibre length of bamboo is generally 2.7 mm, which lies between the average fibre lengths of softwoods (3.7 mm) and hardwoods (1.3 mm) (Chaurasia

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et al., 2016b).

According to the most recent data presented in the Global Forest Resources Assessment 2020 (FRA) by the Food and Agriculture Organization of the United Nations (FAO), bamboo covers approximately 35 million hectares of land in Africa, Asia and the Americas (FAO, 2024). Bamboos are mainly found in tropical and sub- tropical areas as well as in some milder temperate regions, with abundance occurring in East and Southeast Asia and on the islands of the Indian and Pacific oceans. More than 75 genera and around 1250 species of bamboos are reported to occur all over the world. About 80% of the total area of bamboo forests occur in Asia and the Pacific regions (Chen et al., 2019). Bamboos are found both at a variety of altitudes. India ranks second in the extent of bamboo genetic resources, the first being China. The bamboo richness of these countries together accounts for more than half (around 70%) of the total bamboo wealth of the world. About 25% of bamboo species occurring in the world are found in India. They are distributed across all the states but are most prominently found in the Western Ghats and the seven Sister States of North-East India (Sharma and Nirmala, 2015). This study examines the potential use of bamboo in a variety of applications.

2. Bamboo's versatility in industrial applications

Bamboos, amongst the fastest growing plants and with a high yield, are a unique group of grasses that can be used for a variety of purposes. Today, many industries are facing a scarcity of quality raw materials while others are searching for suitable cellulosic waste that can be used as an initial raw material (Ansari et al., 2023; Gupta et al., 2020; Joshi et al., 2015, 2017, 2019; Malik et al., 2020; Rana et al., 2021). The fast growth and high fibre characteristics makes bamboo a suitable and sustainable solution for industrial purposes.

The many uses that bamboo offers have led to the use of terms like "Green Gold", "Poor Man's Timber", "Bamboo, Friend of The People" and "Cradle to Coffin Timber" (Tewari et al., 2019). Bamboo was conventionally considered as a minor forest product but nowadays is recognized as an economically vital plant group by various forestry programmes. The uses of bamboo range from fodder, pulp, timber, construction, charcoal, edible products to cottage industries. Some of the major industrial uses of bamboo are shown in Fig. 1.

Fig. 1. Major industrial uses of bamboo.

Bamboo plays a crucial role in the daily lives of rural and tribal populations. It is used by rural people in construction, the manufacture of farm implements, household utensils and as a food source, especially during rainy season. It is also an industrial plant as it is utilized not only by the pulp and paper industries but also many cottage industries. It is a vital forest product which plays a significant role in the socio-economics of the rural population. Consequently, the development of efficient management techniques could provide benefits at local, national and global levels through livelihood, economic and environmental security for millions of people residing in rural areas. Some commercially vital species along with their uses are depicted in Table 1.

2.1. Bamboo as a raw material for the pulp and paper industry

The pulp and paper industry is regarded as one of the prime industries of the world (Boruah et al., 2019). Increasing environmental concerns and the depletion of natural resources have forced the paper industries to explore alternative raw materials for papermaking. A major concern is to search for potential non-wood fibres that can be utilized as a substitute for woody fibrous raw material. Fast growing species such as bamboo are of interest because of their potential in cellulose and paper industries. They are a source of fibrous raw material for many countries such as India that face a grave raw material crisis. Bamboo is considered as a versatile and indispensable industrial material as it is a source of long fibre raw material for pulp and paper industry.

Bamboo has been used for paper production for centuries in some Asian countries, including China and India. Handmade paper production from bamboo began more than 2000 years ago in China. The inner parts of the bamboo were beaten into a pulp and used in paper production. In India, the Forest Research Institute (FRI) at Dehradun carried out pioneering research on bamboo in the field of pulp and paper when Pearson made an extensive survey of the availability of bamboo in India and William Raitt initiated a study on the development of an efficient and economic process for the preparation of bleached grade pulp from bamboo. Raitt developed a two-stage digestion method for bamboo pulping on a commercial scale. The process was based on the removal of starches, degraded products of sugars, gums, tannins and other colouring materials by mild cooking in the first stage and complete delignification under drastic conditions in the second stage (Casey, 1980; Raitt, 1931).

The total current supply of bamboo in India is estimated at 2–3 million tonnes per annum. The paper industry uses bamboo to meet 60–70% of its total requirements for cellulosic raw materials (Your Article Library, 2023). The global trend towards the widespread commercialization of bamboo products is gaining momentum. However, the surge in demand poses a potential challenge as a scarcity of bamboo resources may impede the growth of the bamboo industry. Moreover, factors such as rapid population growth, expansion of agricultural land and extensive deforestation are contributing to significant pressure on the land available for bamboo cultivation. These combined elements in addition to the disparity between supply and demand present limitations to the sustainable development of the bamboo industry (Li and He, 2019). India, Bangladesh, Thailand, and China stand out as the leading nations globally in utilizing bamboo pulp for paper production, with India at the forefront. For instance, India annually produces an impressive 1233,771.25 tonnes of bamboo pulp for paper-making, while the Indo-China Peninsula, encompassing countries like Thailand, Vietnam, Cambodia, and Myanmar, contributes 816,466.27 tonnes. China follows closely with an annual production of 544,310.84 tonnes. Notably, both China and India are witnessing a rise in bamboo utilization, driven by the need to enhance pulp and paper capacities to meet growing demand (Ogunwusi and Ibrahim, 2022).

Bamboo is a more suitable raw material for papermaking than wood due to its rapid growth, short harvesting cycle (Sekyere, 1994), easy propagation and high productivity. Bamboo is among the many raw materials used for making pulp (Hidayati et al., 2019). It is a quite

Table 1
General information of some commercially important bamboo species.

Bamboo species	Soil type	Climatic conditions	Uses
Bambusa tulda Roxb.	Common on flat alluvial soil along streams in mixed deciduous forests, loamy, fertile and well drained	Tropical to sub-tropical conditions	Pulp and paper, lumber, Agarbatti sticks, handicrafts, food
Bambusa bambos (L.) Voss	Nearly all types of soil having good drainage, however sandy loams, alluvial soils and slightly acidic soils exhibit superior growth	Tropical to sub-tropical conditions	Construction, scaffolding, ladders, furniture, pulp and paper, food and fodder
Bambusa balcooa Roxb.	Grows in wide variety of soil types but heavy textured soil with adequate drainage is most productive	Tropical to sub-tropical conditions	Scaffolding, construction, ladders, Agarbatti sticks, food, paper
Bambusa polymorpha Munro	Well drained alluvial and loamy soils	Tropical to sub-tropical conditions	House construction, woven matting, baskets, furniture, handicrafts, paper, pulp and board making, edible shoots with a distinctly sweet taste, landscaping.
Bambusa nutans Wall. ex Munro	Well drained sandy loam to clayey loam	Tropical	Baskets, fences, roofs and roof tiles, paper, treating inflammation, ulcers and wounds
Dendrocalamus asper (Schult. & Schult.f.) Backer	Well drained black soils, Sandy clay loam or shallow lateritic soil mixed with fine sandy clay. Good drainage is vital.	Sub-tropical to tropical. Suitable for drier zones	High quality edible shoots, construction
Dendrocalamus hamiltonii Nees & Arn. ex Munro	Wide variety of soils with good drainage, sandy loam soils are most suitable	Tropical to sub-tropical	Young shoots are widely consumed as vegetables, construction (houses, bridges), pulp and paper
Thyrsostachys oliveri Gamble	Well drained loamy soils	Tropical	Construction, furniture, baskets, umbrellas, fishing rods, sports goods, edible shoots
Melocanna baccifera (Roxb.) Kurz	Moist sandy, clay loam alluvial soils, well drained residual soils.	Tropical to sub-tropical	Edible shoots, famine food, leaves for brewing liquor, Tabashir - a siliceous concretion found in the culms of the bamboo stem, can be collected from the culms and used as a tonic in treating respiratory diseases.
Dendrocalamus strictus (Roxb.) Nees	Sandy loam soil with good drainage	Tropical to sub-tropical	Pulp and paper, construction, furniture, mats, sticks, baskets, household utensils, food

(Source: Guadua Bamboo, 2023; NBM, 2023; INBAR, 2024)

sought-after raw material used for pulp and paper making in Malaysia, China and India (Ameh et al., 2017). The schematic process of making paper from bamboo is depicted in Fig. 2. Various studies have been conducted on the fibre dimensions and chemical composition of various species of bamboo from different countries as well as on their potential for commercial pulping. However, there are still many species whose potential needs to be explored. The drawbacks of using bamboo as a raw material for pulping and papermaking have been discussed by Chen et al. (2019). The higher ash and silica content of bamboo can pose problems in the recovery process of alkaline spent liquor. Other challenges include the management of bamboo forest plantations, and the higher costs of logging, storage and transportation compared to wood.

2.1.1. Adaptability of bamboo for pulp and paper

Hurter (2002) stated that about 35 species of bamboo serve as a raw material for the pulp and paper industry. He discussed various attributes that make bamboo an important fibre resource for the pulp and paper industry, including:

i. Chipping of bamboo is similar to that of wood.
ii. Bamboo chips can be easily blended with wood chips and their pulping and bleaching can be carried out in wood-based pulp mill equipment.
iii. The required species of bamboo can be produced to meet the specific fibre requirements of the pulp and paper industry through cloning technology which can also help in the redevelopment of depleting bamboo stands.
iv. Bamboo farms enable fast production of bamboo resources to aid industrial development.

The morphological (fibre dimensions) and chemical characteristics (α-cellulose and hemicellulose) are vital for pulp and paper making, as depicted in Table 2 for various forms of lignocellulosic biomass. In addition to this, the quality of the pulp and paper produced will depend on the lignin and holocellulose content (Hartono et al., 2022a; 2022b).

2.1.1.1. Fibre characterization. Egbewole et al. (2015) evaluated the fibre quality of *Bambusa vulgaris* Schrad. ex J.C.Wendl. as a suitable raw material for pulp and paper manufacturing. Their work incorporated the study of various fibre characteristics (such as fibre length and fibre diameter) that exhibited suitability for production of tissue, corrugated materials, newsprint, and writing paper. They found that *Bambusa vulgaris* could be utilized by the pulp and paper industry as a potential source of non-wood fibres. Fibre dimensions are indicative of the fitness of a raw material to produce pulp. Chaurasia et al. (2016b) studied the fibre characteristics of *Melocanna baccifera* in relation to its suitability as a fibrous feedstock for pulp and papermaking. The various fibre dimensions examined included fibre length, width, wall thickness, lumen width/diameter, Runkel ratio, slenderness ratio, flexibility ratio and fibre shape factor. The study concluded that *M. baccifera* also had good potential for papermaking.

The technological characteristics (by determination of basic density, chemical composition and morphology of the fibers) of *Bambusa vulgaris* biomass for pulp production through the Kraft process were assessed and compared with *Pinus* spp. and *Eucalyptus spp.* by Júnior et al. (2019). The pulping process was conducted at 8 different charges of active alkali (viz. 10%, 12%, 14%, 16%, 18%, 20%, 22% and 24%), 1:4 bath ratio (solid to liquor), 25% sulphidity, heating time 90 minutes, highest temperature 170 ℃ and retention time of 60 minutes at the maximum temperature. The results showed the comparable fibre length and wall thickness of *B. vulgaris* fibres. Although the basic density and extractive content was higher, the holocellulose content was lower. Also, *B. vulgaris* could be more easily delignified, consumed lesser alkali and produced fewer rejects. Sekyere (1994) examined the potential of a local variety of *B. vulgaris* in Ghana to act as a raw material for pulp and papermaking.

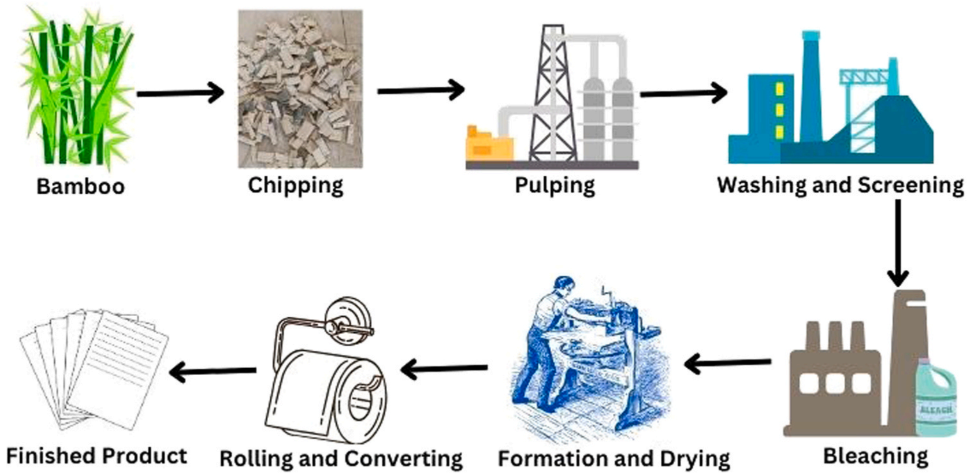

Fig. 2. Schematic representation of paper manufacturing process.

Table 2
Fibre dimensions, chemical composition and pulp yields of different lignocellulosic biomass.

Species	Average fibre length (mm)	Average fibre diameter (mm)	Cellulose (%)	Pentosans (%)	Lignin (%)	Pulp Yield (%) *	References
Softwoods	0.39–3.64	0.027–0.052	40.0–44.0	7.23–12.30	25.70–34.20	38–58	Ahmad et al., 2020; Biermann, 1996; Nayak and Mukherjee, 2015; Rusch et al., 2023; Singh et al., 1992
Hardwoods	0.68–1.84	0.0087–0.830	40.0–44.0	6.13–21.90	18.96–34.60	42–54	
Bamboo	1.01–4.03	0.013–0.016	35.20–51.58	15.13–21.49	21.99–32.20	43.40–54.5	
Agro residue	0.70–3.00	0.010–0.085	30.0–49.1	14.77–26.60	11.30–30.16	34.20–57.50	
Grasses and Reeds	0.78–2.83	0.009–0.038	25–40	14.20–25.45	20.50–31.48	39.1–53.0	

*All pulp yields are of chemical pulping

They found that the fibre characteristics as well as the strength and physical properties of the pulp exhibited good paper making value. Shamsuri and Main (2021) revealed the suitability of bamboo fibre as a substitute for wood fibres in papermaking through chemical analysis, fibre characterization and pulping. Hidayati et al. (2019) examined the chemistry and structural characterization of bamboo pulp with formacell pulping. The formacell pulping process utilizes acetic acid and formic acid as cooking chemicals. These offer many advantages such as high pulp yield, low lignin content, high brightness and good strength. The effect of acetic acid: formic acid on the properties of *Betung* Bamboo (*Dendrocalamus asper*) pulp was studied and it was found that 90:10 acetic acid: formic acid ratio was the best ratio.

2.1.1.2. Chemical characterization. Proximate chemical analysis helps in the determination of the aptness of a material for pulping and papermaking. The biochemical composition of various bamboo species has been depicted in Table 3. Chaurasia et al. (2016a) studied the proximate chemical composition of *Melocanna baccifera* (Muli Bamboo), most commonly found bamboo in North East India, and its suitability for pulp and paper production was determined. *Melocanna baccifera* was found to be a suitable pulping and papermaking material. Gmelina (*Gmelina arborea* Roxb.) and bamboo (*Bambusa vulgaris*), two commonly grown biomass species in Nigeria, were evaluated and compared by Akeem Azeez et al. (2016) for their fibre characteristics and paper properties. The chemical composition and cooking conditions (Chemical/Kraft pulping) of the two were similar. The different growth stages of *Dendrocalamus brandisii* (Munro) Kurz sheaths were explored by Zhan et al. (2017) for their anatomical and chemical properties. The presence of both short and medium-sized fibres in the sheaths of *D. brandisii* and the slenderness ratio makes it a suitable papermaking material. Further, low ash and comparable holocellulose content to other non-wood fibres have also shown good prospects for papermaking.

Kamthai and Puthson (2005) explored the physical properties, fibre morphology and chemical compositions of sweet bamboo

Table 3
Biochemical composition of different bamboo species (Source: Singh et al#, 1992).

Bamboo species	Solubility					Pentosans	Lignin	Cellulose
	Ash	Cold water	Hot water	Alcohol benzene	1% NaOH			
Dendrocalamus strictus	2.10	4.20	5.93	0.25	15.00	19.56	32.20	68.00
Dendrocalamus asper	1.50	6.40	9.20	5.50	24.70	-	28.50	-
Dendrocalamus hamiltonii	1.8	2.47	4.42	0.28	20.81	21.49	26.21	63.26
Dendrocalamus longispathus (Kurz) Kurz	2.45	2.30	5.07	1.22	19.76	19.47	25.54	62.96
Melocanna baccifera	1.87	3.26	6.48	1.43	18.97	15.13	24.13	62.25
Bambusa bambos	3.26	4.59	5.25	0.22	19.35	19.62	30.09	57.56
Bambusa polymorpha	1.67	2.93	6.88	1.70	18.39	21.48	21.99	61.79
Bambusa tulda	2.02	2.64	4.97	1.86	21.80	18.42	24.16	64.36
Ochlandra travancorica (Bedd.) Gamble	2.6	3.59	3.13	2.19	19.98	17.84	26.91	61.76
Gigantochloa nigrociliata (Buse) Kurz	1.25	1.61	3.39	0.24	17.11	17.41	27.09	66.72
Schizostachyum dullooa (Gamble) R.B.Majumdar	1.78	4.99	6.61	3.24	20.48	18.10	23.82	64.64
Gigantochloa scortechinii Gamble	1.30	4.80	5.90	3.40	19.40	-	26.40	-

(*Dendrocalamus asper*) for pulp and papermaking. They found that the properties in a culm varied according to position (top, middle, base) as well as parts (node and internode). They concluded that its fibre is comparable to that of softwoods and has the potential to be used as a feedstock for pulp and paper industries.

In a similar study by Sadiku et al. (2016), the fibre and chemical characteristics of *Bambusa vulgaris* were investigated for their suitability as a sustainable and alternative raw material for pulp and paper making. The study was done on culms of different ages (2, 3 and 4 years) and samples were collected from different positions of the culm (top, middle, base). It was concluded that *B. vulgaris* meets the criteria for pulping and papermaking. The fibre characteristics did not differ with age and position along the culm. However, the chemical properties varied among culms of different ages, with the exception of holocellulose which differed along the length of the culm. They concluded that any part of the culm of any age could serve as a raw material for papermaking. The work carried out by Siregar et al. (2023) encompassed an additional pre-hydrolysis stage prior to pulping and bleaching which resulted in pulp with a lower kappa number and increased brightness of the bamboo, thereby indicating its suitability for manufacturing pulp products.

In another study on *Melocanna baccifera* by Tripathi et al. (2018), pulp and papermaking properties were examined with special emphasis on the chemical composition and physical properties of bamboo chips. They also looked at the pulping and refining behaviour, bleaching response, fibre morphology and strength properties of the bleached pulp. It containe 52.78% cellulose, 21.1% hemicelluloses and 25.2% lignin, similar to the composition of some hardwoods. The fibre length (1.68 mm) obtained after pulping was greater than in hardwoods. Bleaching produced analogous results to hardwood species. The prepared handsheets also exhibited good strength properties. The results suggest that *M. baccifera* could be used successfully for papermaking. Chang et al. (2013) investigated the effect of age (0.2, 1.2 and 3 year-old) of *Bambusa spinosa* Roxb. (syn. *Bambusa stenostachya* Hack.) on its pulping and paper properties. Only young (<1 year) shoots were suitable for pulping and papermaking, with sufficient strength and brightness for production of fine paper. Suhaimi et al. (2022) investigated the impact of different bamboo species viz. *Bambusa vulgaris* (*Aur*), *Gigantochloa levis* (Blanco) Merr. (*Beting*), and *Gigantochloa scortechinii* (*Semantan*) and their age (1, 3 and 5 year-old) on the pulping yields and mechanical properties of the products. They concluded that 1 year old bamboo gave the maximum pulp yields. In a similar work conducted by Yoon et al. (2006) on 60-days, 1-year, 2-year and 3-year-old moso bamboo (*Phyllostachys edulis* (Carrière) J.Houz.; syn. *Phyllostachys pubescens* (Pradelle) Mazel ex J.Houz.) led to the conclusion that pulping yield decreased with an increase in the age of the bamboo culms. Hossain et al. (2022) found that the top portion of a 3-year-old culm of *Melocanna baccifera* had the highest cellulose content (74.7%), which is regarded good for pulp and paper production. There are numerous species of bamboo that have yet to be examined for their potential for pulp and papermaking.

2.1.1.3. Silica content in bamboo - reality or myth?. In the thriving realm of bamboo research and applications in the field of pulp and paper, an intriguing silence exists about the silica content in the innumerable research papers that have been published. Liese and Tang (2015) reported that the silica content in bamboos varies from 1% to 6% and increases from bottom to top with primary deposition in the epidermis while no deposition occurs in the tissues of the internodes. Bamboo contains a lot of silica and this presents difficulties throughout the pulping and papermaking process. Processing equipment may experience greater wear and tear as a result of the higher silica. Although silica is a vital component of ash and considered hostile for paper production, it remains unexplored in the majority of the available literature (Sharma et al., 2011; Tripathi et al., 2018; Júnior et al., 2019; Sadiku et al., 2016). The content of silica in bamboo has sometimes been overestimated and mischaracterized, and so a more accurate understanding of the actual silica content and its implications for the process of paper manufacturing is much needed to clarify the situation.

2.1.2. Writing and printing grades

Tao et al. (2022) prepared holocellulose paper from *Phyllostachys edulis* that exhibited good mechanical properties, printability and degradability. Khantayanuwong et al. (2023) assessed four bamboo species found in Thailand, *Bambusa vulgaris*, *Bambusa longispiculata* Gamble, *Dendrocalamus membranaceus* Munro, and *Thyrsocalamus liang* Sungkaew & W.L.Goh, for their potential to form kraft pulping handsheets, concluding they were a viable resource for paper production.

2.1.3. Packaging

The suitability of the bamboo *Dendrocalamus strictus* for food packaging applications has been investigated by Dhiman et al. (2023). Hasan et al. (2019) and Hermawan et al. (2019) utilized two bamboo species *Schizostachyum brachycladum* (Kurz ex Munro) Kurz and *Gigantochloa scortechinii* to fabricate biodegradable composite packaging films based on seaweed and microcrystalline bamboo cellulose. Ameh et al. (2017) found that the pulp produced by carrying out semi- chemical pulping of *Bambusa vulgaris* had the potential to make corrugated board, carton paper and other industrial papers. Pratima and Purrahoo (2022) discussed the potential of bamboo to form different paper products viz. envelopes, paper bags and holders. The various end uses of different bamboo species have been illustrated in Table 4.

2.1.4. Specialty grade

Bamboo is a promising raw material for the manufacturing of a wide array of specialty papers. The potential of bamboo fibre insulating

Table 4
Bamboo species and their significance to Pulp and Paper Industry.

Bamboo species	End product	Reference
Phyllostachys edulis	Biodegradable packaging tape	Tao et al. (2022)
Dendrocalamus asper	Pulp and paper	Amri and Masrol (2022), Khair and Masrol (2022)
Bambusa vulgaris	Pulp and paper (tissue, corrugating medium, newsprint, and writing paper)	Akeem Azeez et al. (2016), Egbewole et al. (2015), Sadiku et al. (2016), Sekyere (1994), Ogunsile and Uwajeh (2009)
Oldeania alpina (K. Schum.) Stapleton	Pulp and paper	Aklilu (2020)
Oxytenanthera abyssinica (A.Rich.) Munro and Beema Bamboo	Pulp and paper	Boadu et al., (2022)
Melocanna baccifera (*Muli* Bamboo)	Papermaking	Chaurasia et al. (2016a)
Melocanna baccifera	Pulp and paper	Tripathi et al. (2018), Sharma et al. (2011)
Gigantochloa apus (Schult. f.) Munro (Tali bamboo), Bambusa vulgaris (Ampel bamboo)	Wrapping paper	Efiyanti et al. (2018)
Oxytenanthera abyssinica	Pulp and papermaking	Worku et al. (2023)
Gigantochloa scortechinii (Semantan Bamboo)	Enhancing properties of recycled papers for corrugated papers manufacturing	Mohd Hassan et al., (2018)
Bambusa tulda, D. hamiltonii, B. balcooa, B. bambos	Pulp and paper	Sharma et al. (2011)
Drepanostachyum falcatum (Nees) Keng.f.	Electrically conducting paper	Pokhrel et al. (2023)
Phyllostachys edulis	Tissue paper handsheets	Guan et al. (2019)

paper, encouraging the development of green paper industry, has been discussed by Song et al. (2023). Huang et al. (2016) reported the promising utility of bamboo fibre and softwood fibre in combination for manufacturing insulating presspaper. Bamboo as a raw material in furnish consisting of other cellulosic raw materials was utilized for developing various specialty grades such as azure laid ledger paper, alkali resistant paper, barrier paper, padding paper, poster paper, paper cup base paper and seed germination paper (Dutt et al. 2005a; 2005b; 2004; 2003a; 2003b; 2003c; 2003d). Thermal insulation boards with thermal conductivity comparable to conventional insulating material such as lightweight concrete has been prepared from bamboo paper sludge and fly ash floating beads by Zhang et al. (2017). Very soft tissue handsheets were prepared from *Phyllostachys edulis* chemi-thermo mechanical pulp by An et al. (2020).

2.1.5. *Dissolving grade pulp*

Dissolving pulps are the pulps with high purity, brightness, alpha-cellulose but low hemicelluloses and lignin (Wu et al., 2018). Dissolving grade pulp is a vital segment of the pulp and paper industry. The traditional raw materials (cotton linters and wood) used in dissolving pulp production are being replaced by non-wood lignocellulosic raw material owing to the limited availability of woody biomass. The morphology and chemical composition of bamboo offers good pulp properties that render it suitable as an alternative raw material to wood for the production of dissolving grade pulp (Ma et al., 2011). The distinctive properties of dissolving grade pulp include high alpha-cellulose content (> 90%), low hemicellulose content (3–6%) and minute quantities of lignin and other impurities (Chen et al., 2016). Dissolving pulps are utilized for the production of cellulose derivatives such as cellulose nitrate, cellulose acetate, viscose, rayon, methylcellulose and carboxymethylcellulose (Batalha et al., 2012) as shown in Fig. 3. Wood composition is an important parameter that must be taken into account in the production of such pulps. The crucial quality criteria for dissolving pulps include alpha-cellulose content, alkali solubility, degree of polymerization (DP), molecular weight distribution (MWD) and reactivity (Chen et al., 2016). The production costs of dissolving pulp production are quite high due to very low overall fibre line yield that barely surpasses 35% (Li et al., 2015). Nevertheless, the market demand for dissolving grade pulp has risen in recent years (Wu et al., 2018).

An evaluation of commercial bamboo chips as a raw material for dissolving pulp production was carried out by Batalha et al. (2012). The chips were initially subjected to autohydrolysis followed by NaOH/AQ pulping and subsequent bleaching to full brightness. A good quality dissolving pulp with high brightness (92.4% ISO), 94.9% alpha-cellulose content and acceptable levels of hemicelluloses, ash and extractives for viscose rayon production suggested the viability of bamboo chips for utilization as a raw material for dissolving pulp production. The results were compared with eucalypt dissolving pulp produced by a pre-hydrolysis kraft process, with bamboo dissolving pulp being of lower quality and costlier to produce. Cellulose acetate, relevant to the textile and cigarette industries, is manufactured from sources having more than 95% alpha-cellulose. He et al. (2008) prepared a high grade bamboo dissolving pulp from *Bambusa emeiensis* L.C.Chia & H.L.Fung (syn. *Dendrocalamus affinnis* Rendle) for cellulose acetate (acetate bamboo pulp). It was produced by conducting oxygen-alkali pulping, giving xylanase and DMD (an intermediate product of the reaction of oxone with acetone) delignification treatments, and $H_2{}^{\circ}{}_2$ bleaching. The properties and structures were evaluated by various analytical techniques, including FTIR spectroscopy, X-ray diffraction and NMR spectroscopy, and compared with high grade hardwood dissolving pulp for cellulose acetate (known as acetate wood pulp), viscose bamboo pulp and bamboo fibre for textiles. Chen et al. (2016) has discussed the important aspects of dissolving pulp production and mentions the importance of strong cooking and bleaching conditions for good quality dissolving pulp production. Bamboo is considered an ideal source of dissolving pulp owing to its high fibre length, abundance and similar chemical composition to wood. Prehydrolysis preceding the kraft pulping process is regarded as a critical step for obtaining dissolving pulp with high cellulose and low hemicellulosic content (Li et al., 2015).

Li et al. (2015) focused on the importance of improving cellulose yield (which typically halts at 35%) in the dissolving pulp production of bamboo by utilizing dilute acetic acid in the prehydrolysis stage preceding pulping and cold caustic extraction before bleaching. The yield reported was 37%, higher than that obtained with other agents. This was possibly because the acetic acid paced up the process of hemicellulose degradation and enhanced the diffusion of cooking liquor in bamboo fibres.

The compact structure of bamboo, thicker cell wall, high hybrid cell content, wax and high hemicelluloses makes the penetration of liquor difficult. This can be solved by including a pretreatment step prior to pulping. Preparation of dissolving pulp from green bamboo (*Bambusa*

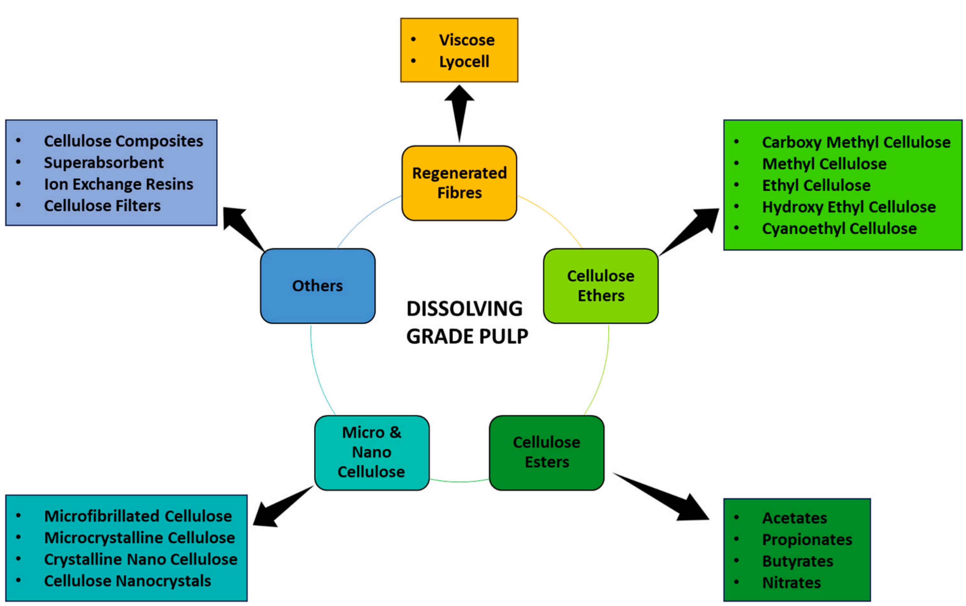

Fig. 3. End product applications of dissolving grade pulp.

oldhamii Munro (syn. *Dendrocalamopsis oldhamii* (Munro) Keng f.) for textile production was carried out by Ma et al. (2011, 2012). Prehydrolysis was done initially using water at high temperature and a low liquor ratio which helped in the loosening of the bamboo structure due to dissolution of the hemicelluloses that eased the penetration of chemicals in subsequent stages. The optimization of prehydrolysis conditions was done in addition to studying the kinetics and mechanism of hemicellulose solubilization during the bamboo hydrolysis. The best conditions reported for hydrolyzing bamboo were 1:3 liquor ratio, heating rate of 5℃/10 minutes, 170℃ cooking temperature and 60 minutes cooking time (Ma et al., 2011). Ma et al. (2012) evaluated the effects of the pulping process variables (alkali charge, sulphidity, cooking time and temperature) on the dissolution of lignocellulosic components (lignin, pentosans and cellulose). The kraft pulping process conditions were optimized for minimum cellulose degradation. It was concluded that an increment in alkali charge and sulphidity resulted in a decrease in kappa number and yield with the alkali charge being more significant than sulphidity.

However, more severe conditions led to more cellulose degradation. Consequently, 23% active alkali charge, 26% sulphidity, 60 min cooking time and 170℃ cooking temperature were determined to be the optimum for selective delignification.

2.1.6. Moulded pulp products

Being completely recyclable and biodegradable, moulded pulp (or fibre molded) products from bamboo are a viable and sustainable substitute to the petroleum-based plastic packaging materials deemed unfit for the environment. Moulded pulp is a product of three-dimensional paper making technology that is made into different shapes of paper products. The suitability of bamboo as a fibre resource for the production of moulded pulp packaging is due to rapid growth, reduced cost and similar chemical composition and fibre properties to wood (Liu et al., 2023a,2023b). Debnath et al. (2022) stated that a typical pulp mould packaging commodity must exhibit certain characteristic features such as moderate resistance to compression, good insulating properties and low density. In recent years, extensive scientific efforts have been dedicated towards harnessing the potential of bamboo for fibre-moulded products. Liu et al. (2020) developed a biodegradable, renewable and environment friendly tableware, an alternative to plastic ones, by blending bagasse and bamboo fibres for food packaging applications. Wang et al. (2021) prepared residual lignin-based pulp lunch boxes (RL-PLB) with significantly higher wet strength from the bamboo species *Bambusa chungii* McClure.

2.2. Bamboo for food and feedstock production

Food scarcity has arisen as a global issue owing to population growth, geopolitical issues and climate change. Bamboo has emerged as a boon to improve food security in both humans and livestock feeds.

2.2.1. Food source for humans

Edible shoots are produced by many species of bamboo. Out of 136 species available in India, the most common edible bamboo species are *Bambusa pallida* Munro*, Bambusa tulda, Bambusa polymorpha, Bambusa balcooa, Dendrocalamus hamiltonii, Dendrocalamus giganteus* Munro and *Melocanna baccifera* (syn. *M. bambusoides* Trin.) (Choudhury et al., 2012). Bamboo shoots have high nutritive value containing low fats and cholesterol but high amounts of carbohydrate, proteins, minerals and dietary fibres. The shoots are consumed as vegetables or used for making pickles (Tamang et al., 2013). Fresh, dried, shredded or pickled bamboo shoots are a traditional cuisine in many parts of the country, particularly the North-Eastern states in India.

Bamboo shoots are a traditional delicacy in many countries including India. In India, the consumption of bamboo shoots is confined mainly to the Northeastern states where it is a very popular food item amongst local people. Different communities consume bamboo in different forms viz. fresh or fermented (Devi, 2013). Bamboo shoots are consumed in raw, canned, boiled, marinated, fermented, frozen, liquid and medicinal forms as they are low in fat, but high in potassium, carbohydrate, dietary fibres, vitamins and active materials (Choudhury et al., 2012; Sangeetha et al., 2015). A number of bamboo shoot fortified products have been reported by Bajwa et al. (2021). Bamboo shoot fibres are in great demand globally for making gluten free products (Silva et al., 2020).

Data on the composition of minerals and vitamins in the shoots of different bamboo species have been compiled by Wang et al. (2020). Freshly harvested shoots contain a significant amount of vitamin A, vitamin B6, vitamin E, niacin, and thiamine. Young bamboo shoots are used as a good source of protein, fibres and calories. A detailed analysis of nutrient composition of different bamboo species has been done by Nongdam and Tikendra (2014). The nutritive properties and medical significance of different bamboo species is given in Table 5. Young shoots of some species of bamboo are utilized as vegetables, pickles and many diverse products in preserved form in the daily meals in countries such as India, China, Japan, Taiwan and Thailand. Bamboo rhizomes (*Acidosasa lingchuanensis* (C.D.Chu & C.S.Chao) Q.Z.Xie & X.Y.Chen*, Bambusa bambos* and others) are also deemed fit for human consumption as they are a rich source of food fibres and antioxidants but low in fat and calories (Bajpay and Yadav, 2019).

2.2.2. Livestock feed

The leaves of bamboo were used as fodder for livestock by the Japanese for hundreds of years. The concentration of fibre and proteins in bamboo make it a good source of food for feedstock. It has potential for winter forage for goats and other livestock. It also reduces the exposure of livestock animals to gastrointestinal parasites, thereby acting as an excellent feedstock. Giant pandas in China survive solely on bamboos and they can consume 19 kg of fresh bamboo leaves per day on an average. Bamboo leaves which provide food for cattle, sheep, goats and chicken can help meet the calcium demand for these animals as bamboo absorbs and accumulates calcium from soil (Sawarkar et al., 2020).

2.2.3. Shelf-life of bamboo

Bamboo shoots, when freshly harvested, have a shelf life of 9 days when stored in water and 23 days when preserved in brine (Choudhury et al., 2012). The shelf life of fresh bamboo shoots is influenced by external factors such as temperature, humidity, microorganisms and storage conditions, as these elements affect the metabolic activities undergoing in the fresh bamboo shoot. To prevent water transpiration and microbial activity, it is necessary to store bamboo shoots under low temperature conditions (Bal et al., 2012). Substantial literature is available on the postharvest quality deterioration and storage of bamboo. A study was conducted by Kleinhenz et al. (2000) to study the impact of storage temperature and different secondary packaging materials on the shelf life of bamboo (*Bambusa oldhamii*) shoots after harvesting. Secondary packaging and a reduction in storage temperature led to an increment in the shelf life of bamboo shoots.

2.3. Bamboo for biofuels and energy production

The rising cost and pressure on fossil fuel reserves such as petroleum in addition to sustainability and environmental concerns have led to research on alternative biofuels that are greener and more sustainable. One such kind is bamboo, which has the potential to replace some conventional fuels. Bamboo is a special source of fuel whether it is dry or having high moisture, mature or immature. The high growth capacity of bamboo, with up to 22–44 Mt of biomass ha^{-1} y^{-1}, makes it a suitable candidate for a wide range of energy products such as charcoal and biogas (Rathour et al., 2022). The suitability of bamboo for fuel production is due to appreciable fuel characteristics such as low ash content, lower heating value and lower alkali index, exceeding the values for many other biomass feedstocks.

Table 5
Characteristics of different bamboo species used as food source.

Species	Properties	References
Bambusa bambos *Oxytenanthera abyssinica*	High levels of potassium which confers protection to human heart by maintaining normal BP and stable heartbeat	Das (2019)
Melocanna baccifera	Rich in fibre which helps in reducing unwanted bad cholesterol level in blood and keeps digestive tract healthy, vitamin rich	Das (2019), Rathour et al. (2022)
Dendrocalamus asper	Rich in dietary fibres, reduced sugar and fat, useful in cookie formulations	Felisberto et al. (2017), Ahmad et al. (2022)
Bambusa vulgaris, Gigantochloa atroviolacea Widjaja, *Dendrocalamus strictus*	Rich in protein, fiber and vitamin C	Raveendran et al. (2020)
Dendrocalamus brandisii, Bambusa bambos	High amino acid content	Bajwa et al. (2021)
Dendrocalamus hamiltonii, Dendrocalamus sikkimensis Gamble ex Oliv., *D. latiflorus* Munro, *D. giganteus*	High level of Vitamin C	Bajwa et al. (2021), Nirmala et al. (2018)
Phyllostachys mannii Gamble	High content of amino acid asparagine which is essential for biosynthesis of glycoproteins; increases resistance to fatigue and ameliorates smooth functioning of liver	Nirmala et al. (2018)
Bambusa bambos	Rich source of sodium mineral necessary for maintaining osmotic balance within cells, regulates level of vitamins	Satya et al. (2012), Rathour et al. (2022)
Bambusa polymorpha	High content of calcium mineral essential for growth of bones, used in preparing pork nuggets	Satya et al. (2012), Ahmad et al. (2022)
Bambusa tulda	Rich in iron that helps prevent anemia and affects brain functioning, acts as fat cutter	Chongtham et al. (2021), Rathour et al. (2022),
Phyllostachys violascens Rivière & C.Rivière	Helps to control weight and improves lipid profile	Ahmad et al. (2022)
Bambusa balcooa	Rich in fibres and vitamins	Felisberto et al. (2017), Rathour et al. (2022)
Oldeania alpina	Used in prebiotic	Rathour et al. (2022)
Fargesia spathacea Franch.	Higher cholesterol-adsorption capacities, prebiotic effects, cholesterol-adsorption activity	Wu et al. (2020)
Gigantochloa manggong Widjaja	Rich in minerals and dietary fibres	Rathour et al. (2022)

2.3.1. Biofuel generation

Bamboo is converted into different kinds of fuels at varying temperature, pressure and other reaction parameters (Sawarkar et al., 2020). The techniques used for the production of fuel include pyrolysis, the most commonly used method for feedstock conversion and for the production of charcoal and pellets, and pretreatment for production of ethanol and methanol (Akinlabi et al., 2017). The production capacity of bamboo exceeds many other biofuel-producing vegetable plants. Owing to the high content of sugars present in the bamboo, it is a suitable feedstock for producing chemicals such as lactic acid and fuel ethanol in addition to being used as fuel in the form of biogas and bioethanol (Emamverdian et al., 2020). The fuel characteristics of bamboo include high calorific and volatile content values with low moisture and ash contents that make it suitable for biofuel generation (Rathour et al., 2022). Bamboo biomass is an exceptional resource for producing electricity as well. Bamboo has the potential to be utilized as a feedstock for bioethanol production due to its higher growth rate and abundance in the tropics. Kuttiraja et al. (2013) investigated the utilization of the processing waste from *Dendrocalamus* spp. as a feedstock for bioethanol production by enzymatic saccharification. About 143 L of bioethanol per dry tonne of bamboo process waste could be generated. Pathak et al. (2015) studied the biomass potential of seven bamboo species, namely *Dendrocalamus strictus, D. asper, Bambusa bambos, B. nutans, B. vulgaris, B. tulda* and *B. balcooa.* These bamboos showed good biomass accumulation capacity that could utilized for the production of biofuels.

2.3.2. Bio-energy products

Bio-energy products derived from bamboo fibre include charcoal, biofuel, pyrolysis, firewood, gasification, briquettes, pellets, and biomass (Imadi et al., 2014). Fuelwood and charcoal made from bamboo, as well as the residues from bamboo harvesting, are renewable in nature. Bamboo charcoal is the solid residue that remains in the pyrolysis chamber. It has a porous microstructure that is primarily composed of carbon. It is a important source of energy for cooking and heating in many tropical and subtropical regions. Bamboo charcoal can act both as a humidifier and as a dehumidifier, depending on the relative humidity as it releases or absorbs moisture from the environment. The charcoal can also be used as a gas adsorbent and in water as well as in air filters. It serves as a purifier of drinking water by removing heavy metal ions. It can substitute for traditional wood charcoal. As the absorption capacity of bamboo charcoal is six times that of wood charcoal, it can also serve as an antibacterial agent that is capable of absorbing bad odours and toxic substances. 1 hectare of cultivated bamboo can produce 31.75 tonnes of charcoal (Sawarkar et al., 2020). A contribution could be made by bamboo biomass to meeting global energy demands through a sustained supply of energy.

2.4. Therapeutic and medicinal potency of bamboo

Bamboo is a plant of immense potential in the pharmacological industry. Almost all parts of the bamboo plant, including the rhizome, culm, leaves, roots and seeds have clinical applications. Bamboo holds great promise for its utilization as a health food because of the presence of bioactive compounds with medicinal properties.

2.4.1. Medical benefits of different bamboo parts

Bamboo shoots have been in use in medicine since time immemorial by Indigenous people in areas where bamboo grows. In the traditional system of Ayurveda, the silicious concretions found in bamboo shoots are called *banslochan* and in the Indo-Persian and Tibetan systems of medicine, they are known as bamboo manna as they are recognized as a good tonic for respiratory disorders (Choudhury et al., 2012). Bamboo shoots are used to control the early phases of cancer infection as lignans and phytosterols in the shoots possess anticancer properties. Young bamboo shoots are used as a good source of protein, fibres and calories. Due to low fat content and presence of essential amino acids, selenium, potassium as well as antioxidant together with minerals, bamboo is considered beneficial for a healthy heart (Bajpay and Yadav, 2019). Stems and leaves of *Bambusa bambos* are used in treating leucoderma, inflammatory conditions, bronchitis, gonorrhoea and fever. Bamboo shoots are also shown to be helpful for weight loss, balancing cholesterol levels and boosting the immune system (Sawarkar et al., 2020). Young rhizomes as well as leaves of many species of bamboo have long been used. Bamboo rhizomes are used for reducing the hot phlegm that coats or obstructs the orifices of the heart that may even affect the functions of the brain (Shukla et al., 2012). The burnt roots help in controlling ringworm, bleeding gums and painful joints (Hossain et al., 2015; Soni et al., 2013). The leaf buds of *B. spinosa* are used to treat conditions such as leprosy and the sap of *B. vulgaris* for phthisis (Borah et al., 2008).

2.4.2. Pharmacological properties

Sangeetha et al. (2015) made a detailed analysis of the therapeutic and pharmacological potential of bamboo. Pharmacological properties of bamboo include antimicrobial, antidiabetic, anti-cancerous, anti-inflammatory and anti-hypertensive roles. Bamboos and their extracts are used in traditional treatments to relieve hypertension, sweating and paralysis. Bamboo extracts have antioxidant and anti-inflammatory properties (Bajpay and Yadav, 2019). Bamboos are also considered to contain high levels of acetylcholine which acts as a neurotransmitter in animals and humans. A phytochemical investigation of the *Phyllostachys* genus has been undertaken by Ibrahim et al. (2021a,2021b). This revealed the presence of a broad range of bioactive compounds. Borah et al. (2008) has mentioned the immense therapeutic benefits of genus *Bambusa*. The therapeutic benefits of various bamboo species are illustrated in Table 6.

2.5. Bamboo for the textile and apparel industry

Bamboo is a renewable resource for clothes and other textile applications. Bamboo fibres are used in the manufacturing of cloth, yarns, and clothing components. Bamboo clothing is made either from 100% bamboo yarn or a blend of bamboo and other fibres. Textiles made from bamboo fibres are renewable and sustainable materials. The advantages of using bamboo as a raw material for textiles include its renewability, biodegradability, efficient space consumption, low water consumption, organic status, and carbon-sequestering abilities, as well as its sustainability. Additional benefits include good hygroscopicity, reflection of light, antibacterial effects and ability to the absorb lesser heat radiation, making bamboo fibres a good raw material for clothing and the production of medical supplies production (Chen et al., 2022).

Manufactured bamboo-fibre textiles are used in bedding, underwear, t-shirts, socks, blankets, towels, and many other textile products. It is being processed together with other fibres such as cotton and polyester to develop new products with greater and longer lasting value. Clothing made with these fibres is comfortable to wear, soft, and can be washed like any cotton cloth (Akinlabi et al., 2017). Ogunwusi (2013) has discussed the various properties of bamboo-based textiles, including comfort, antibacterial and thermal regulating ability, remarkable wicking, good wrinkle resistance, hypoallergenicity, colourfastness, easy care and energy efficiency. Bamboo fibres have excellent characteristics for spinning and weaving (Imadi et al., 2014). Bamboo is an outstanding biodegradable textile material that does not absorb ultraviolet and infrared rays. The textile industry will gain huge benefits from bamboo fibres in the future as bamboo is lightweight, environmentally friendly and bacteriostatic. Liu et al. (2011) developed a chemical extraction method for extraction and modification of natural bamboo fibres for their application in textile manufacturing.

2.6. Bamboo as a substitute for wood

The immense uses and versatility of bamboo helps in its utilization as a potential alternative to timber. Bamboo is considered to be a substitute of wood due to its physical and mechanical properties. Bamboos are endowed with special features such as long fibre length, low proportion of lignin, easy splitting characteristics and flexibility, making it a suitable substitute of wood. Bamboo is increasingly used as a wood substitute in many industrial products such as bamboo plyboard, bamboo mat roofing, door shutters, bamboo mat boards, bamboo flooring, bamboo laminates and particle composites (Borah et al., 2008). The potential of bamboo to serve as an alternative raw material to wood and wood-based composites has also discussed by Chaowana (2013).

2.6.1. Manufacturing material

Bamboo as a manufacturing material is gaining attention in the wood

Table 6
Therapeutic effects of some medicinally important bamboo species.

Species	Part used	Therapeutic effect	References
Phyllostachys edulis	Stems and leaves	Natural anti-oxidative, anti-inflammatory and sometimes antimicrobial activities as well	Nongdam and Tikendra (2014), Das (2019)
Bambusa bambos	Leaves	Anti-inflammatory, antiulcer, antifertility, antimicrobial and anthelmintic properties, antioxidant, hypoglycaemic, antithrombotic activities	Das (2019), Rathour et al. (2022), Gagliano et al. (2022)
Phyllostachys edulis, Dendrocalamus asper, Gigantochloa apus	Shoot skin	Anti-bacterial properties	Das (2019)
Phyllostachys nigra (Lodd. ex Lindl.) Munro	Leaves	cardio protective potential of orientin, anti-inflammatory activity which helps reduce cholesterol (anti-cholesterol) as well as high-density lipoprotein and aids in weight loss	Das (2019), Rathour et al. (2022), Gagliano et al. (2022)
Moso bamboo (Phyllostachys edulis)	Leaves	Anti-diabetic effect	Das (2019)
Bambusa bambos	Pyrolyze extract	Antimicrobial, antifungal, estrogenic effect	Rathour et al. (2022), Gagliano et al. (2022)
Phyllostachys edulis (Carrière) J.Houz.	Shoots	Anti-cancerous properties	Ibrahim et al. (2021a,2021b), Rathour et al. (2022)
Phyllostachys nigra	Leaves	Anti-oxidants, COVID19 inhibitory, anti-cancer, anti-inflammation, cardio-protective	Nirmala et al. (2018), Rathour et al. (2022)
Oldeania alpina	Shoots	Good thiamine, vitamin C, β-carotene and riboflavin contents	Karanja et al. (2015)
Fargesia robusta T.P.Yi *'Pingwu'*	Leaves	luteolin and phenolic acid anti-oxidant compounds	Hoyweghen et al. (2012), Gagliano et al. (2022)
Phyllostachys edulis	Leaves	Anti-oxidants, Antitumor activity, lipid lowering	Nirmala et al. (2018), Rathour et al. (2022), Gagliano et al. (2022)
Bambusa vulgaris	Shoots	Anti-oxidant, anti-microbial, measles and hepatitis treatment	Rathour et al. (2022), Gagliano et al. (2022)
Bambusa tulda	Leaves	Anti-oxidant	Rathour et al. (2022), Pande et al. (2017)
Bambusa balcooa	Leaves	Anti-hyperglycemic, anti-oxidant	Gagliano et al. (2022), Goyal et al. (2017)
Phyllostachys reticulata (Rupr.) K.Koch	Leaves	Immunomodulatory response	Gagliano et al. (2022)

and wood product industries today at the global scale. It has great potential as a substitute for wood as it can be utilized for decorative and shuttering plywood, various board products such as block board, wafer board, strip board, laminated board, roofing sheets, earthquake-resistant and long-lasting conventional housing and buildings, furniture, fuel-wood, charcoal and briquettes, active carbon, matchsticks, incense sticks, tooth picks and skewer sticks. The culms of bamboo are used by local people in the Himalayan states of India for some religious rituals such as prayer flag hoisting. It also serves as an excellent raw material for scaffolding in the construction of buildings and huts used by rural dwellers. In addition to these, bamboos are also used for making plethora of other articles such as mats, fishing rods, baskets, bows and arrows as well as furniture (Tamang et al., 2013). Also, it is used for the construction of bridges in rural areas and making fencing material on farms. Bamboo furniture categories and characteristics have been summarized by Zheng and Zhu (2021). The properties of bamboo and its use as a sustainable environmental material for designing furniture based on the concept of D4S (design for sustainability) has been discussed by Deng et al. (2023). The review done by Anokye et al. (2016) has explained the feasibility of utilizing bamboo materials for boards, blocks and laminations through advanced processing technologies.

2.6.2. Handicrafts

Another important sector where bamboo is being utilized at a large scale is the bamboo craft sector. In India, this activity generates income of 198 million US$ a year and employs mainly women from rural and tribal areas (Borah et al., 2008). The round shape, the smooth skin, the characteristic colour, the texture that originates from the vascular bundles embedded in parenchyma tissue and the node or internode sequence are typical features of bamboo handicrafts (Akinlabi et al., 2017). Bamboo is used in making Lepcha traditional hats (*Sumok thyaktuk*), an old form of craft made by the Lepcha tribe. They are also used for making *chungas* to carry milk and water (Tamang et al., 2013).

The northeastern states in India possess an immense resource of standing bamboo as well having widespread and sophisticated craft skills. This craft-based industry depends on an easily renewable resource such as bamboo. The vast range of products currently being made and used by several tribes living in north-eastern Indian states has been illustrated by Ranjan (1984). The product range includes large structures such as bridges, houses, fences, gates, and bullock carts besides storage bins and a wide variety of baskets used for both for carrying and storage. In addition, devices for fishing, hunting, farming, and weaving as well as products for household use such as furniture, toys, smoking pipes, combs, hats, and musical instruments are exquisitely crafted from bamboo. It also comprises all types of useful items such as kitchen tools and accessories that aid cooking and the presentation of food.

2.6.3. Cottage industries

Millions of tons of bamboos are used in different types of cottage industries such as the agarbatti, kite and cracker industry, ice-cream industry and match industries. Some of the commonly used bamboo species in cottage industries are *Bambusa tulda, B. nutans, B. pallida* and *Melocanna baccifera* (Borah et al., 2008). India is the largest producer of incense sticks in the world. These incense sticks form part of the traditional practice of offering prayers in temples and other places of worship. The major raw materials used in these industries are bamboo, wood charcoal and processed perfumes (Hanumappa, 1996).

2.7. Bamboo for sustainable building and construction

A major proportion of Gross Domestic Product (GDP) in many countries is attributed to the construction industry, often regarded as one of the major pillars of their economies. The increase in construction activities using steel, cement, synthetic polymers and metal alloys has caused environmental degradation as they are polluting as well as being energy intensive in nature (Sakaray et al., 2012). Natural materials such as bamboo have the ability to replace synthetic fibres and conventional steel for building purposes (Chen et al., 2022). Bamboo is considered the world's best naturally engineered material, possessing superior or comparable physical and mechanical characteristics to wood (Hartono et al., 2022c).

2.7.1. Utilization as scaffolding and as a structural element

Bamboo is one of the oldest and most versatile construction materials. The mechanical properties of bamboo culms make them an appropriate choice for load-bearing structures. Bamboo culms from some species possess qualities such as hardness and light weight, suitable for construction purposes. In addition to these, bamboo does not require processing or finishing when used in certain applications (Imadi et al., 2014). Bamboo culms have been used for constructing all types of structures and structural components, such as houses, shelters, boards, roof trusses, wall cladding, pillars, columns, tools, scaffolding, furniture, flooring, ceilings, walls, windows, doors and fences, mostly by rural communities in developing countries. It is an excellent construction material for building houses in disaster-prone areas due to its ability to survive seismic events due to its light weight and elasticity. It even has excellent insulation properties being hollow in nature. Bamboo is regarded as a green material for construction that can be used for many exterior and interior construction purposes such as foundations, fly-overs, dwellings, multistorey buildings, large span structures, and interiors of public buildings. The most appropriate age for using most bamboo species in construction is 3–4 years (Shu et al., 2020).

The various advantages of using bamboo as a construction material include abundant availability, economic nature, light weight, fast growth, higher yield, structural properties similar to steel and concrete, faster construction and a natural sink for carbon dioxide (Fig. 4). On the other hand, there are some limitations, including weak joints and susceptibility to damage by fire and insects existence (Parikh et al., 2016). The culms of bamboo have good strength both in tension and compression. Its tensile strength is nearly equal to that of steel while compression strength is comparable to concrete's compressive strength. The load-bearing capacity of bamboo is twice that of steel and it costs merely 6% of the cost of steel (Sawarkar et al., 2020). Bamboo fibre possesses lignin and hemicellulose (lignin–carbohydrate complex (LCC) in its microfibre structure which gives it a strength greater than concrete and steel by weight, which is due to the thickness of the fibre in the sclerenchymatous tissue (Borowski et al., 2022). A comparison of strength properties of steel and bamboo is shown in Table 7. The short regenerative growth cycle and larger lastingness than gentle steel makes it the most suitable option for construction of earthquake prone buildings (Yadav and Mathur, 2021). It is used as a substitute to steel in construction due to its ability to resist more tension than compression

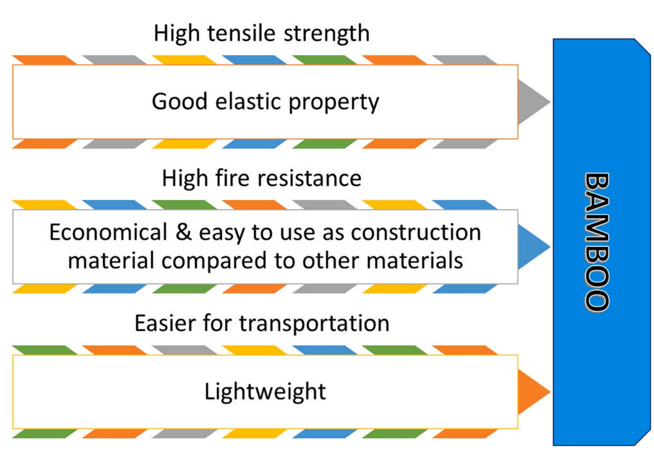

Fig. 4. Benefits of using bamboo as a construction material (Source: Virkhare et al#, 2022).

Table 7
Comparison of the strength properties of steel and bamboo (Borowski et al., 2022).

Properties [kN/cm^2]	Steel	Bamboo
Modulus of elasticity	21,000	2000
Modulus of rupture	20	12.1–20.9
Compressive strength	14.0	6.2–9.5
Tension strength	16.0	14.8–38.4
Bending strength	14.0	7.6–27.6
Shear strength	9.2	2.0

(Onyeka et al., 2019).

Shu et al. (2020) undertook a comprehensive review on the utilization prospects of bamboo-based materials in the domain of construction engineering, focusing on bamboo composition, gradation, material properties, bamboo building components, connection nodes and the use of artificial boards. This natural building material offers several benefits such as outstanding performance, low carbon content, incremental gains in energy-saving and reductions in emissions. Parikh et al. (2016) reviewed the use of bamboo as a sustainable and low-cost housing material in India. Many of the bamboo species available in India are appropriate for construction purposes, such as *Bambusa balcooa, B. tulda, B. nutans, B. pallida, B. polymorpha, Dendrocalamus hamiltonii,* and *Melocanna baccifera* (Borah et al., 2008). The concept of bamboo being a prime green material for use in various industrial sectors including construction was studied by Borowski et al. (2022), who compared the strength properties of steel and bamboo (Table 7). A reduction in the carbon footprint of the construction sector could be achieved by utilizing this fast-growing renewable resource providing a sustainable solution to the current problems associated with construction sector.

2.7.2. Implementation as reinforcement

Bamboo can be efficiently utilized as a strengthening agent in concrete. Sakaray et al. (2012) discusses the various physical (length, weight, number of nodes and culm diameter) and mechanical properties (tensile test, modulus of elasticity, compressive test, pull-out test, shear test and water absorption test) of bamboo in relation to its suitability as a reinforcement material in concrete, As such, it would substitute for steel as the reinforcing material and so they recommended its utilization in green building. The addition of bamboo fibres to the cement paste leads to the formation of bamboo fibre reinforced cement. da Costa Correia et al. (2014) examined the potential of bamboo organosolv pulp as a reinforcement agent in cement-based materials. They found that bamboo organosolv fibres could be a potential replacement for wood fibres in Portland cement-based composites. Bamboo fibre possesses remarkable mechanical properties which on incorporation into concrete augments the physical and mechanical properties of the reinforced concrete (Chen et al., 2022).

In an attempt to seek a greener and more economical construction material, engineers have suggested bamboo as a cost-effective solution to the current problems facing the construction industry. However, the lack of established design standards is a major drawback for the utilization of bamboo in construction projects, despite its superior mechanical performance and long history of use (Shu et al., 2020).

2.8. Bamboo as composites

Composites are structural materials comprising two or more elements combined at a macroscopic level and which do not dissolve into one another. One constituent is called the matrix and the reinforcement is the fibre (Pramudi et al., 2021). Bamboo fibres have the potential to be used as reinforcement in various thermoplastic and thermoset polymers. Thermoplastic materials include high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP) and polylactic acid (PLA), while thermosets include epoxy, polyester and phenolics. The composites can be used as durable consumer goods and for less intensive load-bearing applications. Novel materials can be synthesized by mixing bamboo fibres with different polymers such as polyester-based bamboo fibre reinforced composites, epoxy-based bamboo fibre reinforced composites, phenolic resin-based bamboo fibre reinforced composites, polypropylene-based bamboo fibre reinforced composites, polyvinyl chloride-based bamboo fibre reinforced composites and polystyrene-based bamboo fibre reinforced composites (Chen et al., 2022). Multiple bamboo composites that have been developed over the past four decades, including bamboo scrimber, laminated bamboo, ply bamboo, bamboo strand-based composites and bamboo winding composite pipes (Nkeuwa et al., 2022). Deshpande et al. (2000) reported the extraction of bamboo fibres and their use as reinforcement in polymeric composites. Suhaily et al. (2013) made a detailed analysis of bamboo-based bio-composite materials, their designs and applications. Examples of bio-composite materials that are widely used in manufacturing furniture, in construction, interior design and automotives include medium density fiberboard, plywood and bamboo veneer.

Nkeuwa et al. (2022) have reviewed bamboo composite bonding with respect to bonding characteristics and the associated processes. Guimarães et al. (2015) prepared cellulose nanofibrils from refined/bleached bamboo pulp of *Bambusa vulgaris* by mechanical defibrillation and also investigated their morphological, structural, thermal, optical and viscometric properties with a view to their utilization in biodegradable composites. Cellulose nanofibrils are potential for biodegradable composites due to their unique characteristics such as high surface area/volume ratio, high surface area and strong mechanical properties. The advantages of bamboo fibres, namely low density, light weight and good extensibility, make them a potential candidate for bamboo-based composites such as boards and veneers, and plastic and mineral composites.

2.8.1. Veneers and boards

Bamboo is used for the production of fibre boards (medium density fibreboard and high density fibreboard), particle boards and laminated lumber, veneers, and ply-bamboo. The decline of forest resources is prompting the use of non-wood materials such as bamboo laminated timber (LBT) in many structural and non-structural applications that were previously dominated by wood. Bamboo-laminated products are used in furniture, interior panelling, floor parquet and other products. Yusuf et al. (2018) conducted a critical review of the processing of bamboo culms for use in the production of the plies, particles and pulps that are used in the fabrication of bamboo composites. Hartono et al. (2022b) investigated the suitability of six bamboo species from Sumatera island, Indonesia for composite materials such as laminated bamboo, recommending the use of two species, *Betung* bamboo (*Dendrocalamus asper*) and *Dasar* Bamboo (*Bambusa vulgaris*).

2.8.2. Plastic composites

Bamboo plastic composite (BPC) is a product derived by mixing 60% flour-like powder or very fine particles of bamboo culm with 40% plastic materials (normally PP or PVC) (Akinlabi et al., 2017; Gielis, 2015). Jiang et al. (2020) prepared poly (butylene succinate) (PBS) based biodegradable bamboo plastic composites by using bamboo charcoal powder in order to develop high performance interface compatible bamboo plastic composite products. Pramudi et al. (2021) concluded that bamboo as a natural fibre has the potential to become a composite fibre and bamboo fibre thermoplastic composite is an environmentally friendly material with high tensile strength. Using bamboo fibre in a thermoplastic matrix potentially increases the tensile strength of composites in comparison to other natural fibres.

2.8.3. Inorganic composites

Inorganic bonded bamboo composites play a significant role in the construction industry. Bamboo composites combined with mineral binders can act as a substitute for steel reinforcements (van Dam et al., 2018). Bamboo fibres can be used in construction materials such as cement-based composites. Sakaray et al. (2012) discussed the physical and mechanical properties of bamboo in relation to its potential to act as a replacement for steel reinforcements. Kumar et al. (2021) in their review summarized various studies which used bamboo fibres as a reinforcement in the creation of Fibre Reinforced Composites (FRC).

2.9. Environmental relevance of bamboo

The ecological values offered by these tall grasses cannot be neglected as they help to control soil erosion, protects banks of streams and also help in the reinforcement of embankments and drainage channels. The physical, chemical and biological properties of soils are maintained by bamboos due its abundant litterfall and high biomass accumulation. Bamboos are considered great carbon sequesters owing to their fast biomass accumulation and effective solar energy fixation (Tewari et al., 2019). The ecological functions offered by these tall grasses are depicted in Fig. 5. One hectare of bamboo can consume approximately 15.4 tonnes of carbon every year acting as a beneficial carbon sink (Rathour et al., 2022). These most productive and fast-growing plants have the ability to produce about 35% more oxygen than a similar stand of trees, thereby playing significant role in safeguarding the environment from the consequences of climate change (Yadav and Mathur, 2021). Devi (2013) has described the huge potential of bamboos for fulfilling a number of environmental roles such as soil erosion control, conservation of water, rehabilitation of land and carbon sequestration, which was attributed to the characteristic growth habits of bamboo (especially the interwoven rhizome system). Bamboo helps increase forest volumes, helps in absorbing wastewater from agriculture, industry, animal husbandry, and pollution and plays a crucial role in regional and global carbon (C) cycles (Borowski et al., 2022).

2.10. Life cycle assessment (LCA) studies on bamboo

The life cycle assessment (LCA) method is a valuable tool that considers all input and output streams occurring throughout the manufacturing process (Chang et al., 2018). It is a systematic methodology for quantitatively evaluating the environmental impacts of bamboo-based products during their entire life cycle, beginning from raw material to their disposal and processes involved therein. ISO Standard 14040 outlines the procedures and techniques for conducting Life Cycle Assessments (LCA) (Finkbeiner, 2014). The models used in an LCA illustrate the interconnection between human activities and the environment, highlighting the cause-and-effect relationships and emphasizing the resulting impacts and consequences on environmental systems (Escamilla et al., 2018). Numerous studies associated with bamboo have been conducted in this well-established and continuously evolving field. LCA aims to evaluate quantitatively the ecological consequences, such as greenhouse gas emissions and carbon sequestration (Li et al., 2016; Van der Lugt et al., 2012), associated with the manufacturing and utilization of products over their entire lifespan. A few studies that have applied LCA on bamboo and bamboo-based products are given in Table 8.

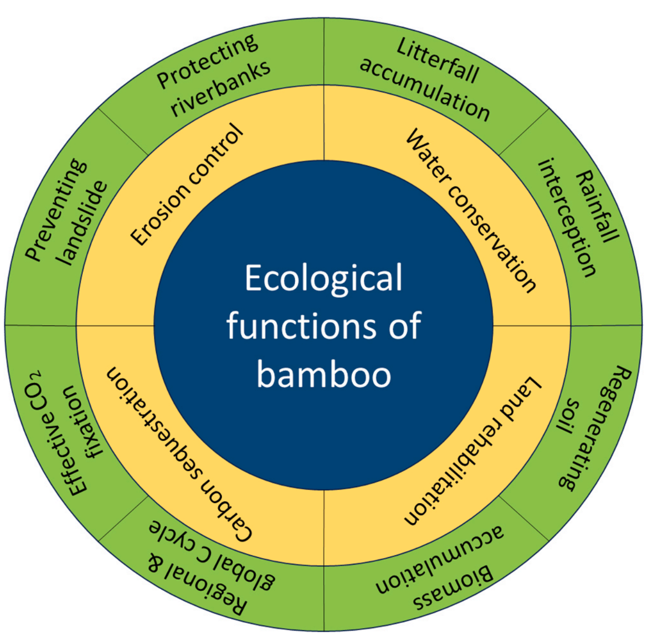

Fig. 5. Ecological functions of bamboo (Source: Ben-Zhi et al#, 2005).

3. Opportunities and bottlenecks in bamboo utilization

Bamboo offers a diverse range of benefits through its utilization at an industrial scale. It is a versatile, sustainable resource with a low water and carbon footprint, possessing strength and durability for multiple applications. Bamboo is renowned for its rapid growth, with some species maturing in less than three to five years (Yadav and Mathur, 2021). It can be harvested without causing long-term environmental damage. Compared to typical plantation tree species, bamboo production frequently uses fewer chemicals, fertilisers, and pesticides, and so has less impact on the environment (Dwivedi et al., 2019). Moreover, bamboo produces a substantial amount of fibre per unit of land area, which might ease the burden on natural forests (Ekhuemelo et al., 2018). The fibres of bamboo have been regarded as strong and long-lasting which can enhance the overall quality and usefulness of products (Khalil et al., 2012). In terms of climate change and global warming, bamboo can effectively trap carbon dioxide, which may assist in climate change mitigation (Lou et al., 2010). Bamboo is known for its exceptional tensile strength, making it suitable for structural applications (Manandhar et al., 2019). Bamboo can be used in a wide range of construction applications, from scaffolding and roofing to flooring and wall cladding (Fahim et al., 2022). Bamboo is often more cost-effective than other construction materials, which can be especially beneficial in regions where it is available abundantly.

Despite being a sustainable and environment friendly biomass, bamboo has some disadvantages. Extensive bamboo plantations have the potential to displace species and natural habitats, Consequently, careful management of its effects on local biodiversity is needed (Canavan et al., 2019). Bamboo is susceptible to pests and diseases, and harvested products are prone to fungi, insects, and decay, obligating the need for adopting preservation methods to increase its durability. Untreated bamboo is more prone to mould and rot in areas that are overly humid or rainy (Kaur et al., 2016). Quality control is another limitation as maintaining consistent quality is challenging; the quality and strength of bamboo can vary depending on factors such as species, age and growing conditions. Its development may be hampered in some areas by a lack of knowledge and uniform building rules for construction purposes (Opoku et al., 2016). Bamboo as a raw material faces competition from other industries that use established materials as their raw materials. Altering the perceptions of people towards bamboo utilization will be a significant task. Management of the supply chain, beginning from cultivation and extending to harvesting, transportation and processing will be challenging. Addressing these challenges will result in the maximization of bamboo utilization at an industrial scale.

4. Conclusion and future prospects

The long-term global impact of deforestation and depletion of natural resources has forced people to find solutions to various problems via research and development. This search has generated the idea of utilizing bamboo as a feedstock for innumerable utilities. Bamboo is a valuable raw material that can be used for many applications and the

Table 8
Studies conducted on bamboo products based on Life Cycle Assessment (LCA).

Bamboo processes and products in LCA	References
Bamboo plywood	Chang et al. (2018), Li et al. (2016), Zhang et al. (2023), Huang et al. (2012)
Bamboo in construction and buildings	Escamilla et al. (2018); Liu et al., (2023a,2023b); Huang et al. (2012)
Thermoplastic and thermosetting bamboo composites	Verma et al. (2021)
Bamboo laminated and scrimber flooring	Yu et al. (2019)
Tableware (Food packaging)	Chen et al. (2023)
Charcoal	Partey et al. (2017)
Bamboo framed cycles	Agyekum et al. (2014)
Bamboo lamps	Bordoloi and Boruah (2022)

usefulness of bamboo as a resource in multiple sectors has been discussed. It offers an excellent opportunity for farmers and related industries to flourish. This 'green gold' is sufficiently cheap and plentiful to meet the vast needs of human populace from the "child's cradle to the dead man's bier". Bamboos have many uses including building materials, paper pulp resources, scaffolding, food, agricultural implements and weaving materials. Its extraordinary performance, sustainability and peculiar properties provide an immense opportunity for growing bamboo-based industries in India, thereby boosting the rural economy. However, the commercialization of bamboo-based products still requires extensive research and knowledge so that the world may benefit from an inexpensive source of fibres.

CRediT authorship contribution statement

Gyanesh Joshi: Writing – review & editing, Validation, Resources, Methodology. **Vikas Rana:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Shuank Malik:** Resources, Investigation, Data curation. **Unnati Chaudhary:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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